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Approach for Measuring Change-Induced Complexity Based on the Production Architecture.

Florian Schoettl*, Max-Christian Paefgen, Udo Lindemann

Technische Universität München, Institute of Product Development, Boltzmannstrasse 15, 85748 Garching, Germany

* Corresponding author. Tel.: +49-89-289-15156; fax: +49-89-289-15144. *E-mail address:* schoettl@pe.mw.tum.de

Abstract

Handling complexity will be a necessity for manufacturing companies to assert themselves against global competitors in highly volatile markets. Therefore complexity is an important target value in planning and operating production systems, because external and internal changes arise more frequently. We show an approach to evaluate complexity induced by changes in the field of production. With a structure-based measure of complexity, system modifications in each lifecycle phase can be analyzed in terms of existing or expected complexity. In order to guarantee high usability, we present an intuitive visualization. The validation is carried out in the automotive industry, where the complexity of developing an engine assembly was examined.

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Keywords: Complexity; measurement; production; architecture; modifications

1. Introduction and problem description

In the series manufacturing of versatile products, complexity plays an increasingly important role as system property that needs to be controlled [1]. In times of global production networks, distributed development departments, as well as frequently changing conditions in terms of customer demands and product aspects, complexity management has moved to the center of attention. In order to use measures of complexity management appropriately, a deep knowledge about the causes and effects of the considered complex problem is necessary. If complexity is to be taken into account as an objective for the initial planning and development of manufacturing systems, assessment methods are required which allow a prediction of future system complexity. During the operational phase, the focus is on the optimization of complexity in terms of CIP (continual improvement process). Thus, a planner needs a prediction of the expected complexity based on the current system configuration, if modifications in the system become necessary.

In summary, we can say that complexity is a relevant objective in each lifecycle phase of the manufacturing system, but different requirements for a measurement approach arise. Due to the variety of dynamic influencing factors and the different perspectives on complex issues, there are few assessment approaches that are sufficiently universal for these applications along the lifecycle and are tested in practice. However, the use of an integrated approach for several applications is a prerequisite for the comparability and validity of the results.

In this paper, we present an approach based on structural system properties in order to evaluate complexity, which is induced by changes and consequently by modifications in the manufacturing system (section 4). Prior to that, a literature review on production complexity and existing measurement approaches is given in section 2 and a definition of "complexity in production" used in our approach is made in section 3. In a final step, a validation of the method using the example of an assembly line for car engines is presented in section 5.

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2. State-of-the-art about complexity research

In this section we present the results of our investigation on methods and approaches to measure and quantify complexity. The basis is a brief overview of complexity definitions in the context of system theory and especially production systems.

2.1. Basic understanding of complexity in production systems

Talking about current challenges in companies of all sectors, the term "complexity" is omnipresent and rated as an increasing problem [2]. For this reason there are all kinds of research activities on complexity with several perspectives, objectives, targets of observation and nevertheless different definitions of complexity. That leads to a huge number of publications dealing with that issue. Because no consistent and established understanding of complexity in terms of production systems exists, we take a system theoretical point of view and focus on structural complexity (cp. [3]). There are basic system parameters or accordingly system properties which interact with the system behavior or rather with the perceived complexity of the system. Figure 1 illustrates these properties.

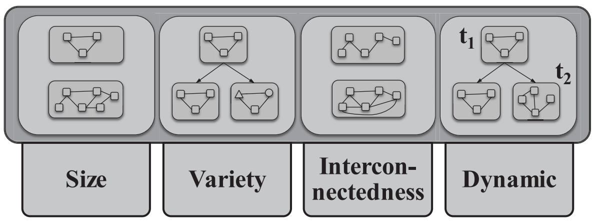

Fig. 1. The basic aspects of complex systems.

In particular, the system size (cp. [4, 5]), the variety of system elements (cp. [2]), the interconnectedness of system elements (cp. [4, 5]), that means the relative number of dependencies [6] and the system dynamic (cp. [4]) are stated. Based on that, Maurer and Maisenbacher [7] as well as Cotsaftis [8] distinguish between simple, complicated and complex systems. Schuh et al. [9] relate that differentiation especially to production systems, whereby complicatedness is not seen as mandatory preliminary stage of complexity. One further aspect in this consideration is the role of the user and his interaction with systems which are called complex (cp. [10, 7]). Schoettl et al. [11] address this aspect and present three cases of system complexity as it is perceived by the user. Consequently, they state that complicated production system or rather the system behavior seems to be complex because of the limited cognitive capabilities. Deif and ElMaraghy [12] argument accordingly and reason that uncertainty is proportional to complexity.

In summary, complexity can be seen as a subjective description of a system respectively of the system behavior which can be based on established structural system properties.

2.2. Approaches for measuring complexity

The outlined problem of an inconsistent understanding of complexity, even in the terms of production systems, leads to numerous measuring approaches of high diversity. Basically three types can be distinguished:

- Product- and variant-based approaches
- Company-wide approaches
- Structure-based approaches

Product- and variant-based assessment approaches deal with complexity, exclusively caused by the variety of manufactured products. Therefore these methods focus on e.g. the numerical investigation of the number of variants as well as the degree of difference between variants. Such investigations can often be found in the field of manufacturing systems (cp. [13, 14, 15]) and are directly related to variant management measurements.

Company-wide approaches have two major objectives. First, balancing the internal complexity of several company departments. Secondly, optimizing the internal complexity under consideration of causing external complexity drivers [16]. The assessment itself is usually based on special key indicators or a subjective assessment of locally perceived complexity. An exemplary application can be found in Voigt and Wildemann [17] for the field of small and middle-size companies or in Schuh et al. [18] for the automotive assembly. They extend that approach to a quantitative measure and assess complexity by a degree of efficiency considering costs and benefit.

Structure-based procedures are based on the postulation that complexity is mainly determinated or even induced by the system structure. That means components, which determinate the system structure, have to be quantified. Scholz-Reiter et al. [19] applied that approach to the logistic of a production system and defined a structure vector in order to measure the complexity.

This overview effectively conveys that only few approaches can directly address complexity in the production. The various dependencies between measurable facts on the product side and negative impact on the production are not described sufficiently. All kinds of interpretations of the effects in terms of complexity are possible. Complexity is often specified by indicators like costs, efficiency etc. but these parameters cannot serve as measure for perceived complexity in the production. Furthermore, no approach can be applied during the whole system lifecycle. In regard to this matter, structure-based methods offer the highest potential. For example the approach from Scholz-Reiter et al. [19] does not include a procedure to assess complexity. The complexity vector is just a target value for further consideration. Finally, there is a lack of a continuous model of the considered object, where causes, effects and structural criteria can be allocated and measured in several phases of the system lifecycle.

3. Complexity in production systems

After a broad overview of definitions and approaches of complexity research considering production systems, we now present the focus of this contribution. First, we describe our understanding of complexity – induced by changes. Secondly, we introduce a model of the production architecture, which enables our complexity measurement approach.

3.1. Change-induced complexity potential

To describe the causes of complexity and their role in the system, we have analyzed a production system at different points of its lifecycle. We got insights from a planer and an operator perspective in interviews and workshops. Production systems are frequently subject to evolutionary modifications, which become necessary due to external changes and volatile boundary conditions. Hence, the system structure (elements and dependencies) has to be modified because changes induce new requirements, which do not fit with the current system configuration. That has two types of implications on operating and planning persons.

New or modified processes and machines increase the perceived complexity. The production as a socio-technical system depends on the abilities and knowhow of employees. They have individual operating experiences and need different periods of training to learn new tasks and processes. During the post-modification phase, when necessary system information is not yet gathered, tasks, processes, related effects and influencing factors cannot be completely surveyed and controlled. To deploy new machines and robots demands for system knowhow in the same way, because decisions about design, configuration and maintenance have to be made by the employees. Once more, deficient information implicates a deficient understanding of processes, machines and their dependencies. Persons interacting with these work stations perceive the missing transparency and unpredictability of the system behavior as complexity.

Furthermore, the modified structure of the production influences the system dynamic. New or modified relations and resulting indirect dependencies of elements cannot be completely surveyed immediately because of the dense interconnection in such production systems. This results in a system behavior, which does not show the expected reaction to the initial input. That kind of missing transparency and unpredictability is perceived as complex, too.

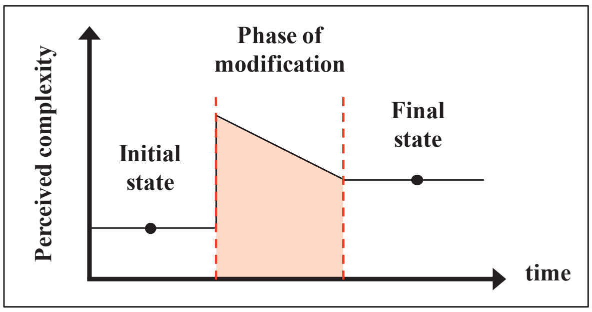

Fig. 2. Perceived complexity of a system modification.

Figure 2 illustrates the qualitative course of perceived complexity over time.

Based on the definitions of Schoettl et al. [11], Deif and ElMaraghy [12] and the findings of this practical study, we put the following thesis, as fundament for measuring the complexity in the production:

Structural modifications in the production system induce increasing perceived complexity. The complexity potential of a modification is proportional to the degree of structural modification.

Thus, we talk about a complexity potential, because the perceived degree of complexity of a modifications depends on the operating experience and the cognitive abilities of the user. That point of view obviously considers only the negative perception of complexity, caused by unexpected system behavior or rather subjective perceived dynamic. Contrary to product applications (cp. [20]), positive aspects of complexity have not been observed in the field of production and consequently there will be no further discussion on them in this paper.

3.2. Meta-model of the production architecture

To represent the versatile modifications on the production system as well as the necessary structural modifications, related reasons and the perceived complexity itself, a continuous model of the production with adequate degree of abstraction is needed. From a system theoretical point of view, the essential domains of a meta-model have to be identified. In accordance with Draht and Schleipen [21] as well as other authors, we define three types of elements "products", "processes" and "resources". Transferring the basic concepts of product architecture to our field of observation results in a meta-model of "production architecture". Enhanced by inter-domain relations between the domains, which are not specified at this point, the schematic system structure follows as depicted in figure 3.

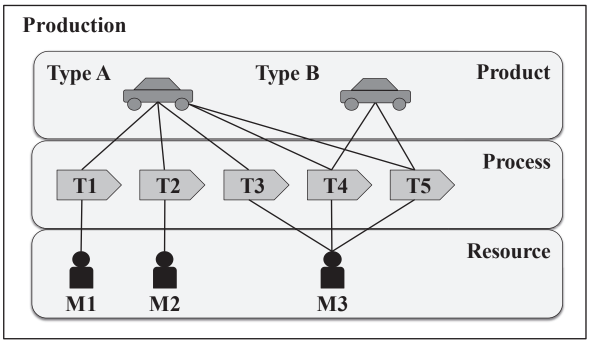

Fig. 3. Meta-model of the production architecture.

With that production architecture all conceivable modifications can be modeled. According to Morales Hernández [22] two different types of variation occur in production systems: "Structure coupling" and "transformation". Transferring these basic types to our meta-model leads us to six concrete types of modifications and related measurement parameters on element level (Table 1):

Table 1. Structural modifications and related parameters.

Type of modification	**Parameter**
Replace / vary processes	Number of new parts
Increase / decrease process variety	Number of alternative parts
Increase / decrease process quantity	Number of parts (mounted at one work station)
Add / remove resources	Number of employees and machines
Adapt resources	- (structural modification are recorded by processes)
Add / remove relations	Degree of interconnectedness *C*: $C = \frac{2n}{k}$ — n: total number of relations; k: total number of elements

Combining these basic types, system modifications can continuously and comparably be modeled in each phase of the production life cycle. Induced changes from the product side e.g. a new part geometry or from the production side e.g. an innovative joining technology can also be allocated in the appropriate domains.

4. Measurement of change-induced complexity

In order to support decision makers in the planning process of a production system, it is essential for them to know the consequences of changes in regard to the perceived complexity. Based on that knowledge, they can decide on whether or not it is necessary to initiate countermeasures such as redesigning parts of the assembly line or decoupling interconnected activities of the assembly process. Also it enables them to compare between different system states at various points in time, which contributes to a better understanding of the evolution process. In this section, a quantitative approach for measuring change induced complexity is presented.

4.1. Quantification approach

Since structural modifications were identified as one main cause of complexity in a production system, we use the six types of modifications that were defined in section 3 to quantify the complexity potential of a system. Various quantifiable parameters are defined and accumulated in a structural vector. The advantage of using a vector is, that the complexity can be described through a multitude of parameters, which allows a more detailed documentation [16]. Furthermore a similar vectorial approach was already used by Costa [23] to describe complex networks.

The vector can be recorded before and after modifications are applied, so that the difference between the two vectors shows how much each parameter has changed. Those values can be listed in a modification vector, which ultimately represents the complexity potential induced. Figure 4 shows the basic concept of the quantification approach.

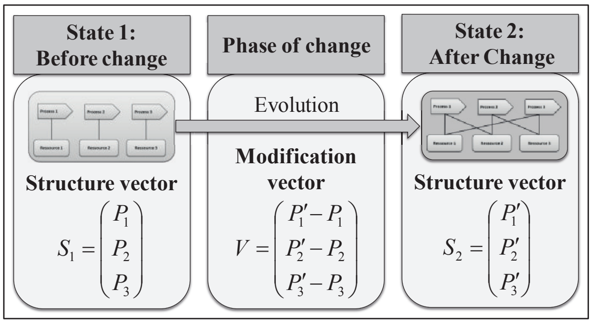

Fig. 4. Measurement approach for change-induced complexity.

For a real-life production system, the types of modification have to be converted to documentable data. Based on the information from table 1, the following measurement parameters on subsystem level were defined:

- Averaged change of process variety per work station
- Averaged change of process breadth per work station
- Average of process variation
- Change of employee count per section
- Change of automatic station count per section
- Change of interconnectedness

In order to apply this concept to a real-life production system, a standardized and transferable procedure with six sequential steps was defined. That enables production planners to analyze previous system modification and compare the results of different production lines:

1. Identification of information sources
2. Definition of modifications
3. Modelling the production architecture before and after a modification
4. Derivation of structure parameters before and after the modification
5. Calculation of the modification vector
6. Visualization of the modification vector in the Absolute-Relative-Portfolio

At first it is necessary to gather possible information sources. Those are different for every application case and need to be taken into account before choosing the parameters. After that, the planned modification of the production system has to be defined. This includes affected areas of the production line time frame for example. It is then necessary to model both states of the production architecture before and after the modification. If the quantification is aiming at modifications that are to be made, a group of specialists is needed to predict the future structure of the production system. Based on the architecture models the parameters can be recorded and the modification vector can be determined. To support a quick and intuitive evaluation of the complexity potential, an "Absolute-Relative-Portfolio" will be used (see subsection 4.2).

4.2. Visualization of production complexity

As the results of the complexity measurement should be intuitive to a broad spectrum of users, a portfolio for the evaluation of the results was developed. For every parameter, the absolute and relative value of the modification in architecture is plotted into a graph. There are three basic patterns that can be recognized in figure 6:

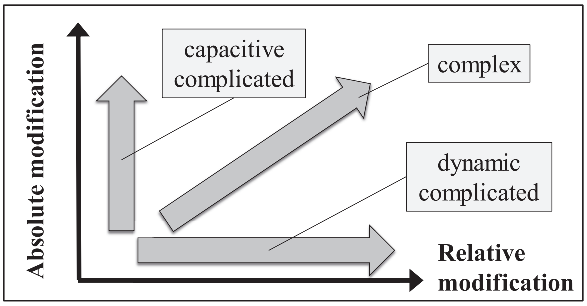

Fig. 5. Absolute-Relative-Portfolio.

Dynamic complicated systems tend to show problems regarding system dynamics combined with unpredictability while capacity complicated systems present with very high levels of interconnectedness linking. Complex modifications combine both effects and are the most critical in terms of system control.

5. Case study

To validate the chosen approach, we applied the quantification method to an engine production line. The desired change was an increase of the output capacity by approximately 40%. The investigated part of the production, is a single line system without parallel work stations. It consists of 16 main processes (labeled as T1 to T16) and 24 initial resources (labeled as M1 to M30). The material flow system between workstations as well as buffers were not taken into account because these items do not influence the system complexity.

Following the procedure of section 4, the first step was to determine accessible information sources. Here a variety of documentation in electronic and printed form was available so that an objective set of data could be used. That database included each modification of processes, resources and relations. So in a next step, the architecture of the production line could easily be modeled. Both system states are shown in Figure 6. The recorded processes with their connections to the resources before the change are depicted in grey color. Modified or added elements and relations are marked in red. In addition to the presented procedure in subsection 4.2 it was necessary to split the production in three section (S_1 to S_3) to raise the significance of the modification vector. Otherwise, the effects of modifications in different areas of the line could cancel each other in the calculation. The defined borders correspond to fixed points of the production process, determined by the product. The values of the modification vector are summarized in table 2:

Table 2. Values of the modification vector.

Structural parameters	S1	S2	S3
Process quantity	-2,3	+0,6	-1,3
Process variety	-2,9	+2,1	-3,1
Number of employees	+2	+3	+1
Degree of interconnectedness *C*:	-0,28	+0,23	+0,14

While each of the parameters described has an influence on the perceived complexity, for this case study we are concentrating on the interconnectedness of the system, because it showed the strongest correlation. The calculated values of interconnectedness are included in figure 2, labeled as C_1 to C_3 in grey and red.

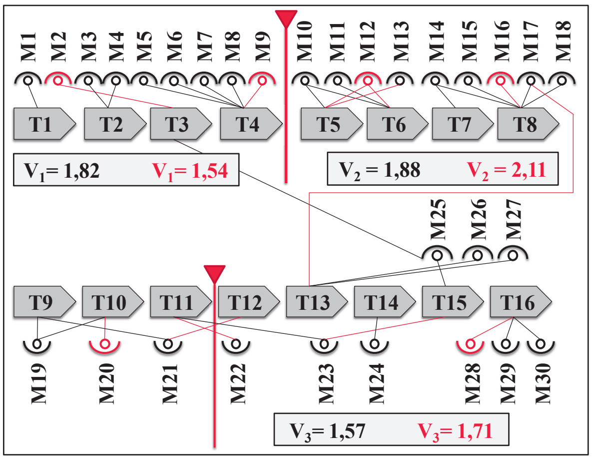

Fig. 6. Architecture of an engine production line.

Figure 7 shows the modification of the interconnectedness plotted in the Absolute-Relative-Portfolio.

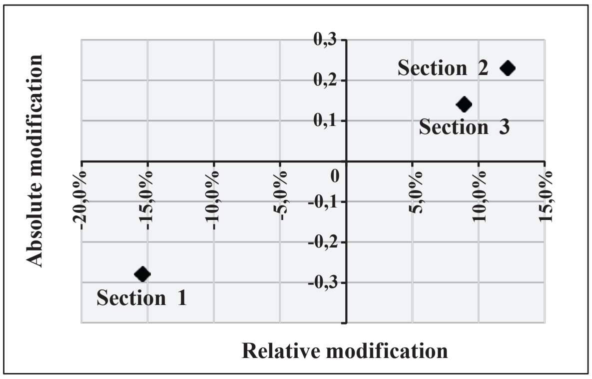

Fig. 7. Absolute-Relative-Portfolio of the interconnectedness.

Section 1 shows a decrease in the degree of interconnectedness and hence an uncritical complexity potential. A comparison of the other two sections leads to the conclusion, that section 2 has the highest complexity potential. It has a degree of interconnectedness of 2,11 to begin with and a relative modification of more than 12%. Therefore it is likely that the system's behavior after the modification will be harder to predict. This is coherent with the observations made at the production line. By increasing the output, working time per station was decreased. Consequently, certain activities have to be split up, leading to an increased number of participating resources and therefore relations. The decrease of interconnectedness in section 1 can be explained by the relatively high increase of work stations.

6. Conclusions and outlook

To consider complexity as a target value in each lifecycle phase, especially in the planning process of production systems, we systematically investigated the occurrence of complexity in terms of changes. After specifying the interplay between the complexity potential, perceived by employees, and the change-induced modifications of the production system, key figures of six different types of modifications were derived. Based on that and a system theoretical consideration of the production architecture, our measurement approach allows a reliable comparison of different system states or rather different production systems. A validation was presented by a use case in the automotive engine production.

In continuative research activities, we will transfer that approach to production systems with alternative structure to confirm its generalizability. Furthermore, the interplay between complexity and other design parameters of production systems like flexibility, efficiency, versatility etc. needs to be investigated. Therefore we plan to enhance the method in terms of complexity avoidance by principles of change-robust design.

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